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Wind power potential assessment of 12 locations in western Himalayan region of India

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ABSTRACT

Wind power potential of a location has to be assessed for its effective utilization. The objective of the present study is to assess the wind resource potential of the western Himalayan Indian state of Himachal Pradesh to identify potential sites along with providing inputs to policy makers for exploiting wind potential of the region for wind power generation and mechanical applications. An overview of current status of wind resource assessment studies is presented to identify suitable techniques. Wind Energy Pattern Factor (WEPF) method is used to assess the wind potential of 12 locations covering different terrains and climatic zones using wind data for the period 2008–2012. Weibull and cumulative wind distributions, Weibull parameters and Wind Power Density (WPD) are determined for these locations. The highest daily mean wind speeds are observed in summers and lowest in winters in the region. Wind shear analysis is carried out which shows that wind speeds at 30 m, 50 m, 80 m and 100 m hub heights are found to increase by 10–17%, 26%, 34% and 39% respectively than those measured at 10 m height. The mean wind speed and WPD for the 12 locations are found to be in the range 3.9–4.7 m/s, 4.7–5.8 m/s, 5.7–7 m/s, 6.2–7.7 m/s and 14.09–22.15 W/m^2, 52.67–82.79 W/m^2, 97.23–152.82 W/m^2, 170.9–268.62 W/m^2, 223.37–351.1 W/m^2 at 30 m, 50 m, 80 m and 100 m heights respectively; thereby indicating fairly good wind potential for rooftop micro-wind turbines, battery charging, water pumping and wind power generation in western Himalayan region. WEPF method is also tested for accuracy. A correlation between measured wind data of Hamirpur and NASA wind data is developed with root mean square error as 0.3855 and R^2 as 92.61% showing that the method has sufficient accuracy. The correlation is used to predict measured wind speeds and power for locations for which measured wind data are not available. Further follow-up research areas are also identified.

Contents

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1. Introduction

Wind is one of the fastest growing renewable energy sources for power generation and has become more competitive with conventional energy sources in recent years [1]. Wind power density expressed in watt per meter square (W/m^2) is considered to be the best indicator to determine the potential wind resource, which is critical to all aspects of wind energy utilization. Wind resource although is highly uncertain due to its stochastic nature, but can be predicted with significant accuracy. The varying nature of the wind speed causes the disturbances in wind power grid connected systems and also affects the stability due to the transients in voltage, current, frequency fluctuations, and power quality issues. This necessitates the need to understand the wind behavior at a location using wind forecast and wind prediction techniques. Wind speed prediction was a part of weather forecasting for many decades which was used for ship navigation, air traffic control, satellite launch etc. However, wind power forecasting has gained importance recently with increasingly use of wind in power generation worldwide.

The wind speed distribution determines the performance of a wind energy generation system for a particular location and time quite well. Once wind speed probability distribution is known, the wind energy distribution can easily be obtained. Therefore, the probability distribution of wind speed is of importance in the wind energy potential assessment. A number of probability density functions are used to describe wind speed frequency distributions but the two parameter Weibull distribution [2] is one of the most widely used tools to determine the variation in wind speed and wind energy potential to assess the commercial viability of wind energy applications. The Weibull distribution is also used as a reference distribution in wind energy software Wind Atlas Analysis and Application Program (WAsP) [3]. The need to carry out wind resource assessment is of importance for a country to harness the available wind energy. Much attention has been given in India for the development of renewable energy resources in early 1980s by establishing a separate Ministry of New and Renewable Energy Sources (MNRE); thus India became the first country in the world to take such a major policy decision of far reaching consequences. Wind energy resource in the country needs to be utilized effectively for energy security, ensuring a sustainable path for the country's economic and social development.

The wind data of India measured at 243 meteorological stations in 13 states are published in seven volumes entitled: Wind Resource Survey in India. Later micro-wind surveys of 97 sites in 10 states were carried out. Major initiative on wind resource assessment was undertaken with the establishment of Center for Wind Energy Technology (C-WET) at Chennai by MNRE in 1998which looks after the development of wind energy program in the country. The wind resource assessment program coordinated by C-WET has covered 31 states and union territories by establishing 1244 wind monitoring and wind mapping stations. 233 potential sites have been identified in the country. CWET has developed Wind Power Density (WPD) map of India at 50 m level based on data from 11 states and 2 union territories.

The potential for wind power generation for grid interaction in India is estimated as 48,500 MW, out of which 43,000 MW lies in Class 2 category with WPD 200–300 W/m^2 and 4380 MW in class 3 with WPD 300–400 W/m^2 and 4380 MW in Class 3 (WPD 300–400 W/m^2) [2]. Indian Wind Atlas, published by C-WET, provides mean wind velocity and mean power density maps of different regions of the India at 50 m and 80 m heights above ground level [4] and has estimated the wind potential for electricity generation in India as 49 GW at 50 m height which has now been re-assessed as 102 GW at 80 m hub-height as shown in Fig. 1.

The development of wind power in India began in 1990s and has significantly increased during last 23 years. The policy support for wind power generation has led India to become the fourth largest installed wind power capacity country in the world over 20 GW during 2013. However, the rate of growth has slowed over the past three years. At present, wind power accounts for about 67% of total renewable energy installed capacity in the country; grid-connected renewable power (29.9 GW) accounts for almost 12.8% of India's overall installed power generation capacity (~232 GW) and accounts for about 5% of electricity generation [5]. The installed capacity of wind power generation in India as up to 31 January, 2014 is 20,226 MW mainly spread across states of Tamil Nadu (7251 MW), Gujarat (3384 MW), Maharashtra (3472 MW), Karnataka (2312 MW), Rajasthan (2734 MW), Madhya Pradesh (386 MW), Andhra Pradesh (648 MW), Kerala (35 MW), Orissa (2 MW), West Bengal (1.1 MW) and other states (3.3 MW). A target of an additional 30 GW of grid connected renewable power is set in the 12th five year plan (2012–2017), of which 15 GW is projected to come from wind power alone [6]. The approved outlay for 12th plan for New and Renewable Energy programmes was INR 33 billion (~ US $ 539million).

Indian market has also emerged as one of the major manufacturing hubs for wind turbines in Asia with annual production capacity of 19 manufacturers offering 50 models of wind turbines with total annual production capacity of over 10 GW and more than 20 wind turbine manufacturing and supply companies are expected to operate by the end of 2014. The government of India has planned to launch

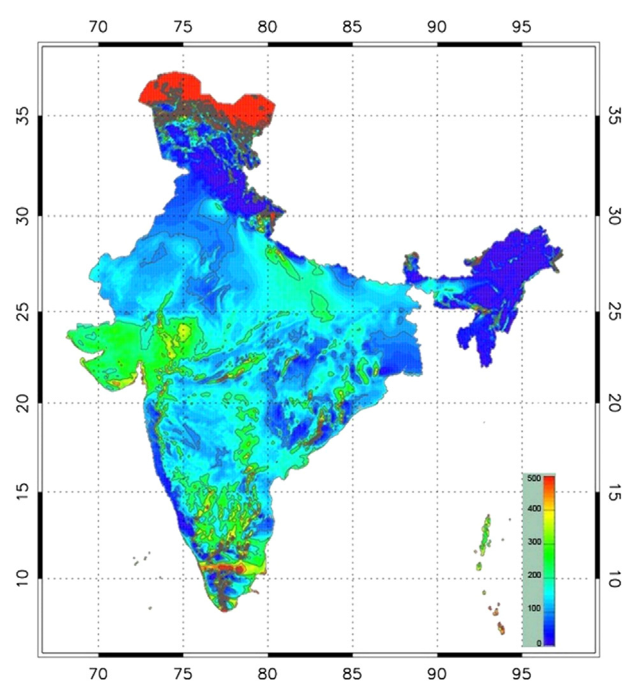

Fig. 1. Wind energy potential of India at 80 m height [4].

Nomenclature

P	wind power density (WPD) (W/m^2)
ρ	air density (kg/m^3)
A	rotor area (m^2)
v	wind speed (m/s)
v_{max}	maximum wind speed (m/s)
v_{min}	minimum wind speed (m/s)
v_i	instantaneous wind speed (m/s)
$\overline{v}$	mean wind speed (m/s)
v_m^3	mean of cubic wind speed
n	number of data points or wind speed measurements
N	number of iterations
$f(v)$	Weibull distribution function
$F(v)$	cumulative distribution function
$p(v_i)$	percentage probability for each winds class
f_i	percentage probability function for each wind class i
W_{v_i}	observed frequency of the wind speed
k	shape parameter (dimensionless)
c	scale parameter (m/s)
α	power exponent
ε_{v_i}	error of the approximation

a National Wind Energy Mission (NWEM) in 2014 which is expected to give a boost to wind power and will enhance development in the wind sector. The Mission aims to have a generating capacity of 100 GW of wind power installed by 2022 by large-scale promotion of onshore and offshore wind power as well as small (< 100 kW) wind turbine systems. Wind resource in the country need to be utilized effectively for energy security, ensuring a sustainable path for the country's economic and social development. Wind energy can easily be used in remote inaccessible areas for both grid linked and off grid applications. With the availability of different capacity micro-wind turbines in the market, there is a vast potential for utilizing them for building integrated applications in near future. However, no systematic wind resource assessment in hilly regions of India including western Himalayan region has been carried out for effective utilization as yet. The main objective of the study is to assess the wind potential at 12 locations covering different terrains and climatic zones in all districts of the western Himalayan Indian state of Himachal Pradesh so as to identify potential sites for various applications of wind energy and to provide further inputs to the policy makers for exploiting the wind potential of the region.

1.1. Description of location

Indian state of Himachal Pradesh is a mountainous state located in western Himalayas between latitudes 30.37°–33.21°N and longitudes 75.76°–79.07°E, with elevation ranging from about 350–6975 m above mean sea level covering geographical area of 55,673 km^2 [7]. The state is divided into three distinct regions with different terrains and climates: Shivalik hills or outer Himalayas, mid Himalayas and greater Himalayas or the alpine zone. Shivalik hills border the state of Punjab and extend to trans-Himalayan region of Zanskar Range, bordering Ladakh and Tibet. The state is divided into 12 administrative districts (Fig. 2). The lower Himalayas include districts of Hamirpur, Kangra, Una, Bilaspur, and lower parts of Solan, Sirmaur, and Mandi with altitude range from 350 to 1500 m. Some parts of Sirmaur, Mandi, and upper parts of Kangra, Shimla, and Chamba districts lie in 1500–4500 m altitude range in mid Himalayas. Kinnaur and Pangi tehsil of Chamba, and part of Lahaul and Spiti district lie in greater Himalayas at altitudes greater than 4500 m.

The paper is organized as follows: an overview of wind speed forecasting and wind resource assessment methods is given in Section 2; the methodology is given in Section 3; the results are presented and discussed in Section 4 followed by conclusion in Section 5.

2. Overview of wind resource assessment methods

In this section, a literature review of wind resource assessment studies is undertaken so as to present research update and to identify suitable techniques for the present study. The wind speed and direction are monitored at a number of potential sites to determine the statistical characteristics of the wind resource in the region. The wind data are used in conjunction with wind turbine power curves to predict the long-term wind energy resource at the proposed site. Wind resource assessment methodology is well established but new approaches are being used. Whereas the wind forecasting deals generally with the prediction for shorter periods, the wind resource potential assessment deals with the annual energy production. In this section we present a brief overview of both the techniques.

2.1. Wind forecasting methods

Wind power forecasting is of great importance for the supply and demand in grid connected wind electricity systems. A number of accurate and reliable wind speed and power forecasting models using different approaches have been developed. The current update status of advances in wind power forecasting models has been presented in recent reviews by a number of researchers [8–11]. Here we summarize some important highlights of these studies. Wind forecasting for energy generation mainly focuses on the immediate short-term of seconds to minutes, short-term of hours up to two days, and the medium term of 2–7 days and long term prediction using different models. The wind forecasting models are divided into two main categories: physical numerical

Fig. 2. Location map of Indian state of Himachal Pradesh.

based approach and statistical models. The physical models use meteorological parameters, terrain features, height, roughness, and obstacles, in the physical equations to estimate variables like temperature, wind velocity, relative humidity, and pressure etc. These models are generally utilized by national weather forecasting services due to complexity and requirement of large resources. Some professional companies also provide the forecasting services.

Statistical models use meteorological data and then forecast the future wind speed and power output and thus involve only one-step to convert the input variables into power output. The statistical techniques generally used are autoregressive (AR), moving average (MA), autoregressive moving average model (ARMA), and autoregressive integrated moving average model (ARIMA), Box–Jenkins methodology, Kalman filtering and Artificial Neural Network (ANN) etc.[8–11]. The Kalman filtering algorithm is applied to filter out systematic errors. ANN is one of the widely used statistical approaches for wind speed and power forecasts.

The hybrid models, which combine physical and statistical approaches or combine short term and medium-term models, are also being increasingly used in recent research.

The literature review indicates that there exist a number of methods for the prediction of wind speed and power. Each method has its own advantages and disadvantages and most of the prediction models developed are generally site-specific and influenced by change in prediction times. However, it is difficult to identify the best model because each model is generally site dependent. Thus, a forecasting model which may perform well at a particular site, may not present accurate results for another site. One has to identify a suitable model as per data characteristics of the site and application.

2.2. Wind resource assessment methods

The wind power potential assessment is generally based on long time meteorological observations in the region of interest. Landberg et al. [12] in a comprehensive review have presented a detailed methodology for the wind resource assessment of a region leading to preparation of wind atlas for the region. Wind resource assessment in a number of countries is carried out with sufficient accuracy using two parameter Weibull wind distribution based models some of which are discussed in this section to identify a suitable technique for the present study.

Aggarwal and Chandel [13] emphasized the need for utilization of wind resource in the state of Himachal Pradesh for electricity generation and other applications but no major initiative has been taken as yet. The preliminary wind resource assessment for a few locations in the state at 10 m height was carried out by CWET which indicates a low wind potential for the state of Himachal Pradesh. However, these locations were randomly identified without any detailed preliminary resource assessment, thus missing many locations which may have high wind potential. Ramachandran and Shruti [14] have carried out preliminary assessment of the wind potential of Himachal Pradesh which requires to be further followed up by a detailed wind resource assessment program for the state after identifying suitable windy locations. In another study Gautham and Ramchandran [15] have identified potential wind energy applications using synthesized wind data and validated with long term surface wind measurements available for some locations.

Akdag and Dinler [16] presented a method known as power density method or Wind Energy Pattern Factor (WEPF) method to determine the Weibull parameters and also established the accuracy of the method in comparison to other methods [16]. Jacovides et al. [17] have carried out statistical analysis of wind speed and direction data for five selected meteorological stations at the Cyprus Coast using Weibull and cumulative distribution techniques showing prospects for low and medium wind energy applications in the south-eastern coastal zone. Katinas et al. [18] investigated wind flow characteristics, current status and future prospects of wind energy use and power generation in Lithuania. A long-term wind data (1945–1990) for 19 meteorological stations and measurements at the sites identified the most suitable region for wind turbine farms is the 10 km wide coastal strip near the Baltic Sea. The average annual wind velocity is found to be 6.4 m/s at 50 m above ground level for the installation of the first wind turbine in the Baltic Sea area of Lithuania.

Kitaneh et al. [19] carried out wind resource analysis using Weibull distribution and Wind Energy Pattern Factor (WEPF) method for five locations in Palestine.

Mathaba et al. [20] analyzed the wind profile using two years time series measured wind data with 10 min interval at Let_seng-la-Terae in Lesotho using Graphical Method and Method of Moments. Wind velocity distribution and optimal Weibull parameters are estimated (shape parameter, $k=1.76$, and the scale parameter, $c=6.71$ m/s) at 10 m above ground level. The determined air density at the site is found as 0.875 kg/m^3 using temperature and the pressure measurements. Oyedepo et al. [21] estimated the wind energy potential of three locations in south-east Nigeria using measured data at a height of 10 m and studied the performance of 50 and 1000 kW wind turbines for electricity generation and a 0.36 kW windmill for water pumping. Carvalho et al. [22] carried out wind resource assessment of two sites in Portugal using mesoscale modeling and wind resource analysis tool namely Wind Atlas Analysis and Application Program (WAsP) and compared the measured results with simulated results.

Several methods have been used to estimate Weibull parameters. Graphic method, maximum likelihood method, and moment methods are commonly used to estimate Weibull parameters. Chang [23] reviewed six numerical methods: Method of moments, empirical, graphical, maximum likelihood, modified maximum likelihood and wind energy pattern factor methods for estimating Weibull parameters and concluded that the WEPF method is better than empirical and graphical methods in estimating Weibull parameters if data number is smaller. The maximum likelihood method performs best followed by the modified maximum likelihood and moment methods. Maatallah et al. [24] carried out analysis of the hourly mean wind speed with a 10-min time step in the central coast of the gulf of Tunis and determined the wind energy characteristics. In order to identify the Weibull parameters, four different methods are used assessing the potential for wind power generation.

Keyhani et al. [25] carried out the statistical analysis of measured wind speed data of eleven years (1995–2005) of Tehran, Iran to identify the wind energy potential and found that the highest wind power potential is in April and the lowest in August. The site is found suitable only for battery charging, and water pumping applications.

Kumaraswamy et al. [26] determined the wind potential of Aimangala in Karnataka and found maximum power density as 829.73 W/m^2 in monsoon season and minimum of 186.15 W/m^2 in winter season. The seasonal variation of wind speed and wind density is also studied. Sanusi and Anisole [27] carried out wind energy potential assessment of Lagos in Nigeria using the WEPF method. Using these methods wind speed and power potential assessment have been carried out by a number of researchers in different countries [28–32,34].

A summary of the comparison of highlights of some of the statistical methods to assess wind speed and power potential of a location is presented in Table 1.

Based on the literature survey the Wind Energy Pattern factor methodology is identified suitable to be used for wind resource assessment in the present study.

Table 1
Comparison of various methods to estimate the WPD by evaluating Weibull parameters k and c.

S. No	Reference	Model	Features	Relations for Weibull parameters
1	[16,23–25,34]	Maximum likelihood method	I. Maximum likelihood method needs extensive numerical iteration II. Maximum likelihood estimates can be heavily biased for small samples. The optimal properties may not apply for small samples. III. Maximum likelihood can be sensitive to the choice of starting values. IV. Most widely used technique among parameter estimation techniques, asymptotically efficient and also unbiased	$k=\left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k}-\frac{\sum_{i=1}^{n}\ln(v_i)}{n}\right]^{-1}$ $c=\frac{1}{n}\left(\sum_{i=1}^{n} v_i^k\right)^{1/k}$
2	[23,34].	Modified maximum likelihood method	Can be used if wind speed data in frequency distribution format are available	$k=\left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)f(v_i)}{\sum_{i=1}^{n} v_i^k f(v_i)}-\frac{\sum_{i=1}^{n}\ln(v_i)f(v_i)}{f(v\geq 0)}\right]^{-1}$ $c=\left[\frac{1}{f(v\geq\ \sim 0)}\sum_{i=1}^{n} v_i^k f(v_i)\right]^{1/3}$
3	[34]	Equivalent energy method	In this method k and c parameters are determined with the help of error of the approximation	$\sum_{i=1}^{n}\left[W_{v_i}-e^{-\{(v_i-1)[\Gamma(1+(3/k))]^{1/3}/(v_m^3)^{1/3}\}^k}+e^{-\{(v_i)[\Gamma(1+(3/k))]^{1/3}/(v_m^3)^{1/3}\}^k}\right]=\sum_{i=1}^{n}(\varepsilon_{v_i})^2$ $c=\left[\frac{v_m^3}{\Gamma(1+3/k)}\right]^{1/3}$
4	[19,23,34].	Graphical method	I. Implemented by fitting a straight line to wind speed data using the concept of least squares, where the time-series data must be sorted into bins II. Parameters are estimated with the regression line equation by using cumulative density function. III. Regression requires that a straight line be fitted to a set of data points, such that the sum of the squares and the distance of the points to the fitted line are minimized.	Taking a double logarithmic transformation, the equation of cumulative distribution function can be rewritten as $\ln\{-\ln[1-F(v)]\}=k\ln(v)-k\ln(c)$ Plotting $\ln(v)$ against $\ln\{-\ln[1-F(v)]\}$ Slope of the straight line fitted best to data pairs is shape parameter and the scale parameter is then obtained by the intercept with the y-coordinate.
5	[21,23,34].	Momeny method	I. One of the oldest of the estimation methods. II. For estimation of Weibull parameters first and second moments of distribution around zero are used III. Equates sample moments to parameter estimates; has the advantage of simplicity; disadvantage is that they do not have the desirable optimality properties of maximum likelihood and least squares estimators. the moment method IV. Primary use of moment estimates is as starting values for the more precise maximum likelihood and least squares estimates.	$\overline{v}=c\Gamma\left(1+\frac{1}{k}\right)$ $\sigma=c\left[\Gamma\left(1+\frac{2}{k}\right)-\Gamma^2\left(1+\frac{1}{k}\right)\right]^{1/2}$ where $\overline{v}=\left[\frac{1}{n}\sum_{i=1}^{n} v_i\right]$, $\sigma=\left[\frac{1}{n-1}\sum_{i=1}^{n}(v_i-\overline{v})^2\right]^{1/2}$ and $\Gamma(X)=\left[\int_0^\infty t^{x-1}\exp(-t)dt\right]^{1/2}$
6	[21,23,25,34]	Empirical method	Empirical method is a special case of moment method	$k=\left(\frac{\sigma}{\overline{v}}\right)^{-1.086}$, if $1\leq k\leq 10$ and $c=\frac{\overline{v}}{\Gamma(1+\frac{1}{k})}$
7	[16,23,24,27,34]	Wind Energy pattern factor method	I. WEPF (E_{pf}) is calculated from the available time series wind speed data (mean monthly and annual values). II. Higher values of EPF are associated with lower wind speeds and lower values with higher wind speeds. III. A useful parameter to calculate the available energy in the wind from mean annual or monthly wind speed. IV. Useful while choosing locations with limited wind data as long-term data from neighboring stations can be correlated with on-site short-term measurement.	$E_{pf}=\frac{\overline{v^3}}{\overline{v}^3}$ $k=1+\frac{3.69}{E_{pf}^2}$

				V. WEPF varies between 1 and 4
8	[24]	Cumulative probability method	Used to find the percentage probability function $p(v_i)$ for each wind class when the frequency of each wind class f_i is known	Cumulative probability function: $F(v_j)=\sum_{i=1}^{j} p(v_i),\ p(v_j)=\frac{f_i}{\sum_{i=1}^{N} f_i}\frac{f_i}{n}$ where $=1,2,3\ldots N$

3. Wind resource assessment methodology

Wind speed is an important random variable which determines the wind energy potential of a site. However, wind is not steady at any site as it is influenced by the incoming solar radiation, regional and local weather systems, terrain, and its height above the ground surface. Wind speed and direction generally vary by minute, hour, day, season, and year wise at a location. In order to assess the wind power potential, it is necessary to carry out long term meteorological observations for the region. Although long-term measurements are expensive yet are essential to be undertaken to create a reliable wind data base. Generally more than 10 years average wind data are required for assessing the wind potential of the site with greater confidence. The wind speed pattern generally is found to repeat over a period of 1 year as it is driven by the sun and climatic conditions during different seasons. In case long term data for a location are not available then the short-term data of at least 1 year can be used. This data can be compared with the long-term measured data from a nearby site to predict the long-term annual wind speeds for the site of interest. This is known as the measure, correlate, and predict (mcp) technique [2]. The monthly wind data averaged over a year are mostly used to describe wind potential of various sites but this data can underestimate the actual wind resource potential of a location as important periods of high or low wind speeds are averaged out. The 1-min time is an appropriate time-averaging period for accurately identifying actual wind speeds. 10-min average wind speed also hides wind speed variability during the period. The 1 min and 10 min average wind speed data are found to provide more accurate picture of wind potential than the average monthly data especially for the regions which may have low wind potential.

Wind speed in a given period can be represented by a probability density function. Wind resource assessment is the first step to identify wind potential of a location for wind energy applications and requires analysis of wind characteristics. The wind speed is a random variable and to determine the wind potential of a region statistical analysis can be carried out. This requires the existence of time series records of wind speed data. Based on the wind speed data collected, the Weibull distribution can be described as a probability density function and a cumulative distribution function.

The geographical distribution of wind speed, wind direction and topography is essential for wind resource assessment. Wind being a highly intermittent resource, its accurate assessment is essential to estimate energy production for a potential site. The basic approach for a reliable wind resource assessment of a region is to carry out

Table 2
Five years mean wind speed range for 12 locations of Himachal Pradesh, India at 10 m height.

S. No.	Location	Latitude	Longitude	Altitude (m) (above m.s.l)	Daily mean wind Speed range (m/s)	5 Years mean wind speed range (m/s) (2008–2012)
1	Keylong	32.58°N	77.03°E	3080	0.89–9.98	2.84–2.99
2	Kalpa	31.53°N	78.25°E	2960	0.8–8.14	2.97–3.1
3	Shimla	31.10°N	77.17°E	2054	0.68–6.01	2.5–2.82
4	Bilaspur	31.33°N	76.75°E	673	0.71–8.44	2.34–2.56
5	Chamba	32.57°N	76.13°E	996	0.77–6.68	2.47–2.61
6	Dharamsala	32.22°N	76.31°E	1457	0.77–6.68	2.47–2.61
7	Hamirpur	31.68°N	76.52°E	785	0.71–8.44	2.34–2.56
8	Kullu	31.96°N	77.01°E	1279	0.68–6.01	2.5–2.82
9	Mandi	31.72°N	76.92°E	1044	0.71–8.44	2.34–2.56
10	Nahan	30.55°N	77.3°E	932	0.66–8.17	2.64–2.97
11	Solan	30.92°N	77.12°E	1502	0.66–8.17	2.64–2.97
12	Una	31.49°N	76.28°E	369	0.71–8.44	2.34–2.56

preliminary study by looking for names of villages, towns, important landmarks, folklores related to wind and using trees/vegetation as wind speed and direction indicators [12]. The inputs from people residing in the region are also important for the preliminary identification of locations with high wind speeds. The potential sites are then identified using wind resource maps, field visits and data from nearby meteorological stations. The methodology results in identifying the suitable windy locations which could be identified for a detailed resource assessment. The micro-site analysis of such potential sites is to be done using on-site wind data monitoring by installing a mast with anemometer, wind vane, temperature, pressure and solar radiation sensors with automatic data acquisition system. The data are then analyzed for key characteristics relevant to wind power conversion which results in identifying the true wind potential for power generation and mechanical applications. A wind atlas of the region can be prepared using data based on long term wind measurement analysis.

In this section we describe the methodology followed in the present study.

3.1. Wind energy pattern factor method

A number of statistical methods are used for wind resource analysis for wind energy applications. The wind energy pattern factor [WEPF] method or wind power density [WPD] method is used to determine wind power potential of various locations using averaged data of wind speed [16]. WEPF method is found to be an adequate to estimate Weibull parameters with sufficient accuracy. The advantage of the method is in its simple formulation as it does not require binning and solving linear least square problem or

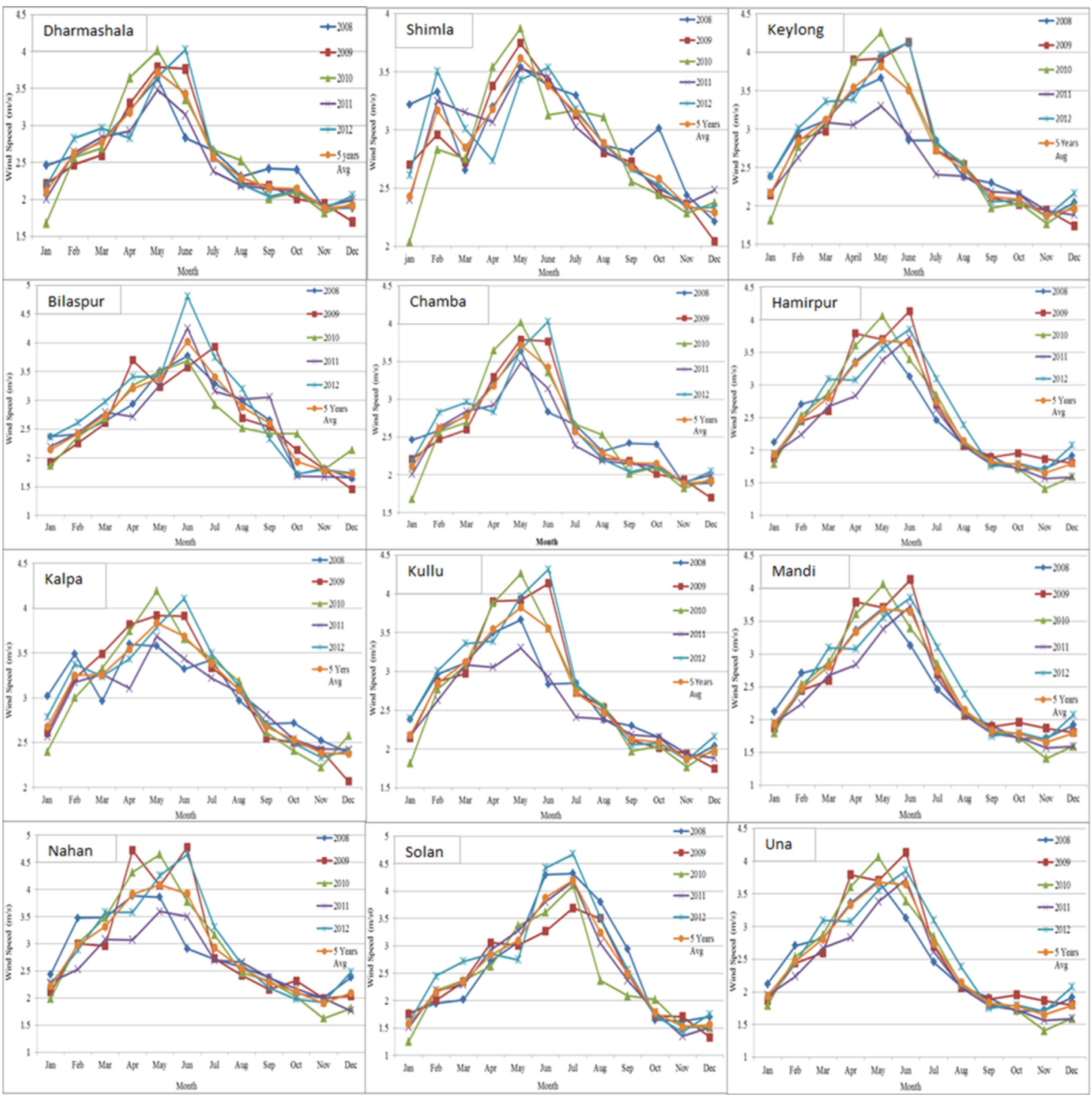

Fig.3. Monthly mean wind speed variations at 10 m for 12 towns of Himachal Pradesh during five years (2008–2012) period.

iterative procedure. Weibull parameters can easily be estimated if mean wind speeds and power density for the location are available. However, the daily mean wind speeds give an underestimation of the true mean power density, as such will not determine power density accurately. An important characteristic of wind power conversion is the non-linear relationship between wind speed and the available power. The wind resource at a location can roughly be described by mean wind speed, but the WPD provides a true indication of a site's wind energy potential.

WPD is the amount of power available in a unit area of the air perpendicular to the flow of the wind. The power in the wind at speed (v) with a blade swept area (A) increases as the cube of its velocity and is given by

$$P=\frac{1}{2}\rho A v^3 \tag{1}$$

where p is the WPD (W/m^2), ρ is the air density (kg/m^3) which depends on altitude, air pressure, and temperature, v is the wind speed (m/s) and A is the rotor area (m^2). The value of air density at sea level is taken as 1.225 kg/m^3.

Wind speed is highly variable so the average of the cube of different wind speeds will be much greater than the cube of the average speed. Therefore, a correction factor known as Wind Energy Pattern Factor (WEPF) or cube factor can be introduced in Eq. (1) for improving the accuracy as

$$\mathrm{WEPF}=\frac{1}{n\overline{v}^3}\sum_{i=1}^{n}\overline{v_i{}^3} \tag{2}$$

where v_i is the instantaneous wind speed (m/s), $\overline{v}$ is the mean wind speed (m/s), and n is the number of data points. If a wind turbine cannot optimize its energy extraction dynamically, the WEPF value is less than one. The value of WEPF can be between zero and four. The WEPF is also be defined as follows:

$$\mathrm{WEPF}=\frac{\text{Average of the cubes of wind speeds}}{\text{Cube of the average of wind speeds}}=\frac{\overline{v^3}}{\overline{v}^3} \tag{3}$$

Therefore, Eq. (1), the mean WPD at a location can be expressed in terms of WEPF as

$$P=\frac{1}{2}\mathrm{WEPF}\rho v^3 \tag{4}$$

The wind speed frequency distribution is an important factor in assessing the wind potential of a region. Weibull distribution is found to fit recorded wind data and is widely accepted for evaluating local wind load probabilities. Weibull and cumulative probability density functions are widely used for wind speed distribution for a typical site to determine wind power potential. The main limitation of the Weibull density function is its inability to accurately calculate the probabilities of observing zero or very low wind velocities. Weibull parameter distribution function does not address the differences of wind velocity variation during the course of a day however Weibull distribution gives a good match with the measured wind data.

Weibull distribution is characterized by two parameters: the shape parameter k (dimensionless) and scale parameter c (m/s). The Weibull density function $f(v)$ and cumulative probability density function $f(v)$ are given as

$$f(v)=\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k-1}\right] \tag{5}$$

$$F(v)=1-\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{6}$$

The WEPF method is used to calculate the Weibull parameters k and c using following equations:

$$k=1+\frac{3.69}{(\mathrm{WEPF})^2} \tag{7}$$

$$\overline{v}=c\Gamma\left(1+\frac{1}{k}\right) \tag{8}$$

where Gamma function is defined as

$$\Gamma(X)=\int_0^{\infty} t^{x-1}\exp(-t)dt \tag{9}$$

3.2. Wind shear analysis

Wind shear describes the variation of wind speed with height. The wind velocity increases with height up to a certain elevation

Table 3
Annual mean, maximum and minimum wind speeds at 10 m for towns of Himachal Pradesh.

S. No.	Town	Daily wind speed (m/s)	Year wise wind speeds (m/s)					
			2008	2009	2010	2011	2012	Mean
1	Keylong	v_m	3.00	2.87	2.84	2.89	2.91	2.9
		v_{max}	6.79	6.84	8.51	9.98	7.84	7.99
		v_{min}	1.23	0.93	0.89	1.41	1.39	1.17
2	Kalpa	v_m	3.06	3.08	3.07	2.97	3.11	3.06
		v_{max}	6.55	5.66	7.62	8.14	6.03	6.8
		v_{min}	1.60	0.81	0.80	1.50	1.57	1.25
3	Shimla	v_m	2.67	2.75	2.71	2.51	2.83	2.69
		v_{max}	5.04	5.69	6.01	5.58	5.52	5.56
		v_{min}	1.26	0.71	0.68	1.11	1.39	1.03
4	Bilaspur	v_m	2.47	2.57	2.48	2.34	2.56	2.48
		v_{max}	5.85	5.72	8.44	5.15	6.17	6.26
		v_{min}	0.82	0.73	0.71	0.94	1.02	0.84
5	Chamba	v_m	2.59	2.56	2.59	2.48	2.61	2.57
		v_{max}	5.55	4.88	6.68	6.21	6.63	5.99
		v_{min}	1.07	0.83	0.77	1.17	1.27	1.02
6	Dharmasala	v_m	2.59	2.56	2.59	2.48	2.61	2.57
		v_{max}	5.55	4.88	6.68	6.21	6.63	5.99
		v_{min}	1.07	0.83	0.77	1.17	1.27	1.02
7	Hamirpur	v_m	2.47	2.57	2.48	2.34	2.56	2.48
		v_{max}	5.85	5.72	8.44	5.15	6.17	6.26
		v_{min}	0.82	0.73	0.71	0.94	1.02	0.84
8	Kullu	v_m	2.67	2.75	2.71	2.51	2.83	2.69
		v_{max}	5.04	5.69	6.01	5.58	5.52	5.56
		v_{min}	1.26	0.71	0.68	1.11	1.39	1.03
9	Mandi	v_m	2.47	2.57	2.48	2.34	2.56	2.48
		v_{max}	5.85	5.72	8.44	5.15	6.17	6.26
		v_{min}	0.82	0.73	0.71	0.94	1.02	0.84
10	Nahan	v_m	2.85	2.94	2.89	2.64	2.98	2.86
		v_{max}	6.40	7.73	8.17	6.35	6.41	7.01
		v_{min}	0.87	0.66	0.82	1.06	1.01	0.88
11	Solan	v_m	2.85	2.94	2.89	2.64	2.98	2.86
		v_{max}	6.40	7.73	8.17	6.35	6.41	7.01
		v_{min}	0.87	0.66	0.82	1.06	1.01	0.88
12	Una	v_m	2.47	2.57	2.48	2.34	2.56	2.48
		v_{max}	5.85	5.72	8.44	5.15	6.17	6.26
		v_{min}	0.82	0.73	0.71	0.94	1.02	0.84

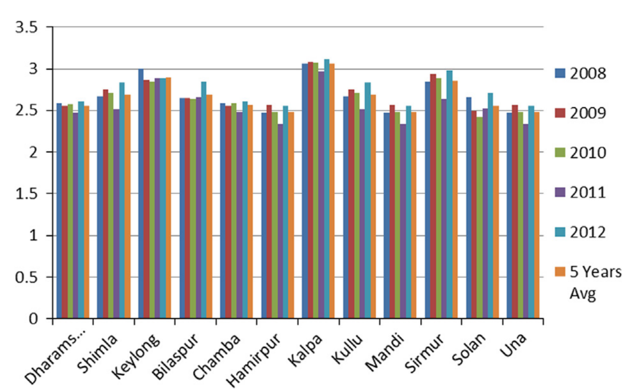

Fig. 4. Variation of annual mean wind speeds at 10 m height for 12 locations of Himachal Pradesh.

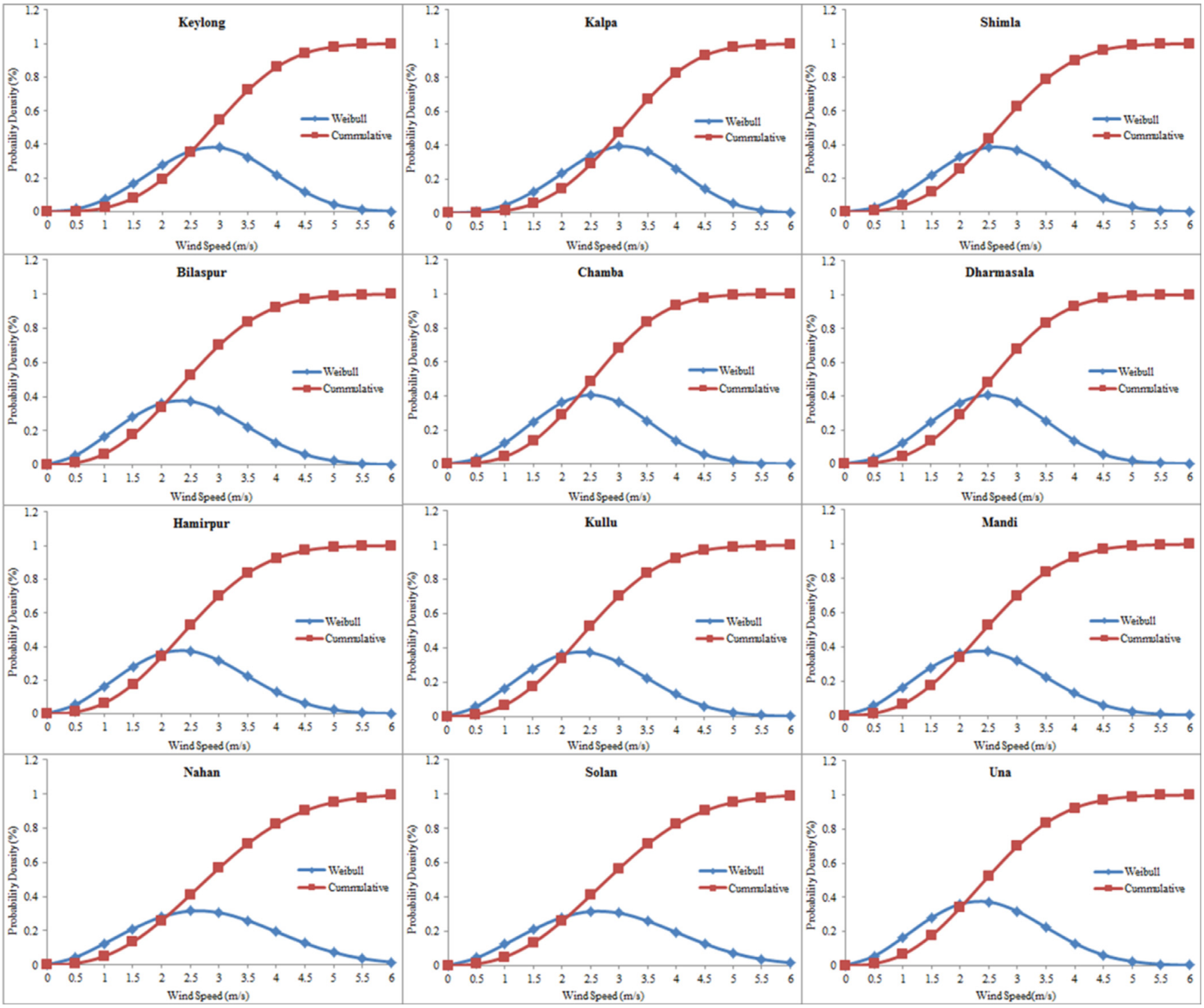

Fig. 5. Variation in Weibull and cumulative probability wind density functions.

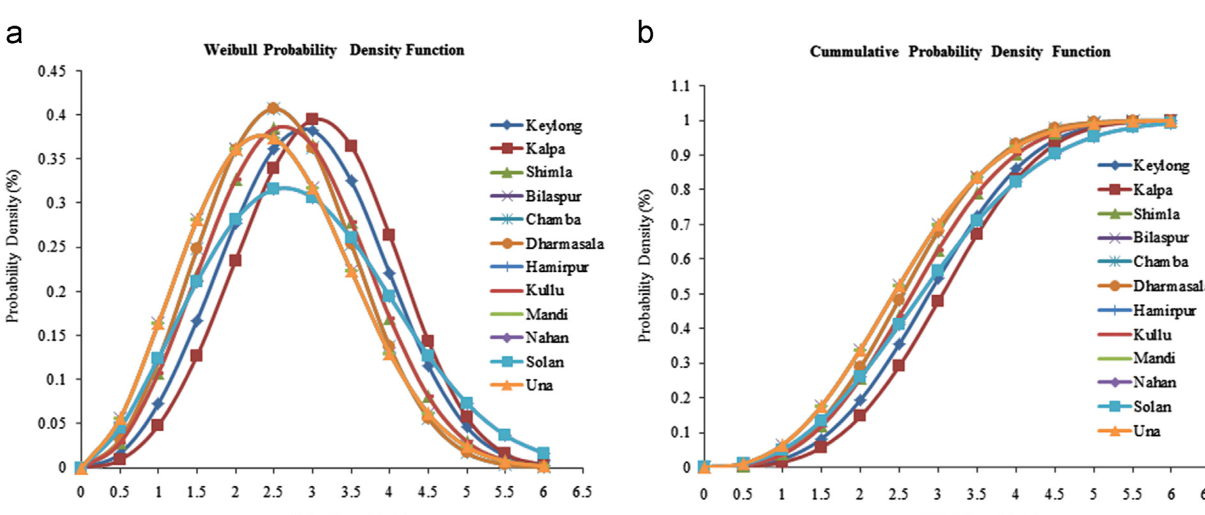

Fig. 6. Comparison of Weibull and cumulative probability wind density functions for all towns in Himachal Pradesh.

and the rate at which the velocity increases with height depends on the roughness of the terrain. The vegetation, trees, forests, and buildings around the location slow down the wind speed. The smooth terrains do not have much effect on the wind speed. The variation in wind speed with height is important for both the assessment of wind resource and design of wind turbines [32]. The wind turbine power output depends on the wind speed at the turbine hub height; therefore it is important to determine wind resource at hub height for accurate estimation of annual energy production. When the Weibull distribution is used to characterize the wind resource, long term hub height values of the Weibull parameters are also required to be determined. Generally wind data collection is done at a height of 10 m but wind turbines available in the market are at various standard hub heights: 20 m, 30 m, 50 m, 80 m, 100 m and 120 m and higher for power generation. It adds extra cost of the tower to take the measurements at these desired heights. The wind speed at the required height can be determined using wind shear models namely log law and power laws.

The power law equation [2] is given as

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{10}$$

where v_1 and v_2 are the mean wind speeds at heights h_1 and h_2 respectively. The value of the exponent α depends on surface roughness and atmospheric stability. Numerically, the value of α lies between the range of 0.05–0.5; the value of 0.143 (1/7th power law) is used for flat terrains [2]. In this study, the power exponent is taken as 0.4 which is found suitable for the complex hilly terrain of Himachal Pradesh [15].

4. Results and discussion

4.1. Wind power potential at 10 m

The wind potential assessment at 10 m height is carried out for 12 towns of Himachal Pradesh using 5 years daily time series NASA wind data for the period 2008–2012 [33]. The monthly, annual variations, wind shear analysis, WPD and Weibull parameters are determined using WEPF method. The daily mean wind speed range and five years mean wind speed range at 10 m height are shown in Table 2.

The monthly variation of daily mean wind speed variations during 2008–2012 for 12 towns in Himachal Pradesh is shown in Fig. 3.

Table 4
Variation of annual mean wind speeds, Weibull parameters, wind energy pattern factor and power density for 12 towns of Himachal Pradesh at 10 m height.

Year	Parameters	Locations											
		Keylong	Kalpa	Shimla	Bilaspur	Chamba	Dharamsala	Hamirpur	Kullu	Mandi	Nahan	Solan	Una
2008	v (m/s)	3.00	3.06	2.67	2.47	2.59	2.59	2.47	2.67	2.47	2.85	2.85	2.47
	WEPF	1.26	1.18	1.28	1.42	1.29	1.29	1.42	1.28	1.42	1.42	1.42	1.42
	k	3.33	3.67	3.25	2.84	3.21	3.21	2.84	3.25	2.84	2.83	2.83	2.84
	c (m/s)	3.34	3.39	2.98	2.77	2.89	2.89	2.77	2.98	2.77	3.19	3.19	2.77
	v_{mp} (m/s)	3.00	3.11	2.66	2.38	2.57	2.57	2.38	2.66	2.38	2.74	2.74	2.38
	v_{me} (m/s)	3.85	3.82	3.45	3.34	3.36	3.36	3.34	3.45	3.34	3.86	3.86	3.34
	P_d (W/m^2)	20.80	20.58	14.87	13.02	13.74	13.74	13.02	14.87	13.02	20.06	20.06	13.02
2009	v (m/s)	2.87	3.08	2.75	2.57	2.59	2.59	2.57	2.75	2.57	2.94	2.94	2.57
	WEPF	1.28	1.23	1.42	1.52	1.34	1.34	1.52	1.42	1.52	1.67	1.67	1.52
	k	3.24	3.44	2.83	2.59	3.05	3.05	2.59	2.83	2.59	2.32	2.32	2.59
	c (m/s)	3.20	3.42	3.08	2.89	2.90	2.90	2.89	3.08	2.89	3.31	3.31	2.89
	v_{mp} (m/s)	2.86	3.10	2.64	2.39	2.54	2.54	2.39	2.64	2.39	2.60	2.60	2.39
	v_{me} (m/s)	3.71	3.91	3.72	3.60	3.42	3.42	3.60	3.72	3.60	4.34	4.34	3.60
	P_d (W/m^2)	18.55	21.90	18.02	15.73	14.29	14.29	15.73	18.02	15.73	25.96	25.96	15.73
2010	v (m/s)	2.84	3.07	2.71	2.48	2.59	2.59	2.48	2.71	2.48	2.89	2.89	2.48
	WEPF	1.30	1.25	1.45	1.61	1.42	1.42	1.61	1.45	1.61	1.69	1.69	1.61
	k	3.19	3.36	2.76	2.42	2.83	2.83	2.42	2.76	2.42	2.29	2.29	2.42
	c (m/s)	3.17	3.41	3.04	2.80	2.90	2.90	2.80	3.04	2.80	3.26	3.26	2.80
	v_{mp} (m/s)	2.82	3.07	2.58	2.24	2.49	2.49	2.24	2.58	2.24	2.53	2.53	2.24
	v_{me} (m/s)	3.70	3.92	3.71	3.59	3.51	3.51	3.59	3.71	3.59	4.29	4.29	3.59
	P_d (W/m^2)	18.28	22.05	17.62	15.07	15.07	15.07	15.07	17.62	15.07	24.89	24.89	15.07
2011	v (m/s)	2.89	2.97	2.51	2.34	2.48	2.48	2.34	2.51	2.34	2.64	2.64	2.34
	WEPF	1.34	1.23	1.28	1.49	1.34	1.34	1.49	1.28	1.49	1.37	1.37	1.49
	k	3.06	3.43	3.25	2.67	3.05	3.05	2.67	3.25	2.67	2.98	2.98	2.67
	c (m/s)	3.24	3.31	2.80	2.64	2.77	2.77	2.64	2.80	2.64	2.96	2.96	2.64
	v_{mp} (m/s)	2.84	2.99	2.50	2.21	2.44	2.44	2.21	2.50	2.21	2.58	2.58	2.21
	v_{me} (m/s)	3.82	3.78	3.24	3.25	3.27	3.27	3.25	3.24	3.25	3.52	3.52	3.25
	P_d (W/m^2)	19.86	19.86	12.38	11.75	12.51	12.51	11.75	12.38	11.75	15.47	15.47	11.75
2012	v (m/s)	2.89	3.11	2.83	2.56	2.61	2.61	2.56	2.83	2.56	2.98	2.98	2.56
	WEPF	1.29	1.20	1.35	1.44	1.37	1.37	1.44	1.35	1.44	1.51	1.51	1.44
	k	3.21	3.57	3.01	2.77	2.96	2.96	2.77	3.01	2.77	2.62	2.62	2.77
	c (m/s)	3.23	3.45	3.16	2.88	2.93	2.93	2.88	3.16	2.88	3.35	3.35	2.88
	v_{mp} (m/s)	2.88	3.14	2.77	2.45	2.55	2.55	2.45	2.77	2.45	2.79	2.79	2.45
	v_{me} (m/s)	3.76	3.91	3.75	3.50	3.49	3.49	3.50	3.75	3.50	4.16	4.16	3.50
	P_d (W/m^2)	19.16	22.00	18.71	14.91	15.01	15.01	14.91	18.71	14.91	24.39	24.39	14.91
Mean	v (m/s)	2.90	3.06	2.69	2.48	2.57	2.57	2.48	2.69	2.48	2.86	2.86	2.48
	WEPF	1.29	1.22	1.37	1.50	1.36	1.36	1.50	1.37	1.50	1.55	1.55	1.50
	k	3.20	3.49	2.98	2.64	2.98	2.98	2.64	2.98	2.64	2.54	2.54	2.64
	c (m/s)	3.24	3.40	3.01	2.80	2.87	2.87	2.80	3.01	2.80	3.22	3.22	2.80
	v_{mp} (m/s)	2.88	3.08	2.63	2.33	2.51	2.51	2.33	2.63	2.33	2.64	2.64	2.33
	v_{me} (m/s)	3.77	3.87	3.58	3.46	3.41	3.41	3.46	3.58	3.46	4.05	4.05	3.46
	P_d (W/m^2)	19.33	21.28	16.32	14.09	14.12	14.12	14.09	16.32	14.09	22.15	22.15	14.09

Table 5
Annual wind speeds (m/s) at different heights for 12 towns during the period 2008–2012.

Year	Height (m)	Locations											
		Keylong	Kalpa	Shimla	Bilaspur	Chamba	Dharmasala	Hamirpur	Kullu	Mandi	Nahan	Solan	Una
2008	10	3.0	3.1	2.7	2.5	2.6	2.6	2.5	2.7	2.5	2.8	2.8	2.5
	20	4.0	4.0	3.5	3.3	3.4	3.4	3.3	3.5	3.3	3.8	3.8	3.3
	30	4.7	4.7	4.1	3.8	4.0	4.0	3.8	4.1	3.8	4.4	4.4	3.8
	50	5.7	5.8	5.1	4.7	4.9	4.9	4.7	5.1	4.7	5.4	5.4	4.7
	80	6.9	7.0	6.1	5.7	6.0	6.0	5.7	6.1	5.7	6.5	6.5	5.7
	100	7.5	7.7	6.7	6.2	6.5	6.5	6.2	6.7	6.2	7.1	7.1	6.2
2009	10	2.9	3.1	2.7	2.6	2.6	2.6	2.6	2.7	2.6	2.9	2.9	2.6
	20	3.8	4.1	3.6	3.4	3.4	3.4	3.4	3.6	3.4	3.9	3.9	3.4
	30	4.5	4.8	4.3	4.0	4.0	4.0	4.0	4.3	4.0	4.6	4.6	4.0
	50	5.5	5.9	5.2	4.9	4.9	4.9	4.9	5.2	4.9	5.6	5.6	4.9
	80	6.6	7.1	6.3	5.9	6.0	6.0	5.9	6.3	5.9	6.7	6.7	5.9
	100	7.2	7.7	6.9	6.4	6.5	6.5	6.4	6.9	6.4	7.4	7.4	6.4
2010	10	2.8	3.1	2.7	2.5	2.6	2.6	2.5	2.7	2.5	2.9	2.9	2.5
	20	3.8	4.0	3.6	3.3	3.4	3.4	3.3	3.6	3.3	3.8	3.8	3.3
	30	4.4	4.8	4.2	3.8	4.0	4.0	3.8	4.2	3.8	4.5	4.5	3.8
	50	5.4	5.8	5.2	4.7	4.9	4.9	4.7	5.2	4.7	5.5	5.5	4.7
	80	6.5	7.0	6.2	5.7	5.9	5.9	5.7	6.2	5.7	6.6	6.6	5.7
	100	7.1	7.7	6.8	6.2	6.5	6.5	6.2	6.8	6.2	7.2	7.2	6.2
2011	10	2.9	3.0	2.5	2.3	2.5	2.5	2.3	2.5	2.3	2.6	2.6	2.3
	20	3.8	3.9	3.3	3.1	3.3	3.3	3.1	3.3	3.1	3.5	3.5	3.1
	30	4.5	4.6	3.9	3.6	3.8	3.8	3.6	3.9	3.6	4.1	4.1	3.6
	50	5.5	5.7	4.8	4.5	4.7	4.7	4.5	4.8	4.5	5.0	5.0	4.5
	80	6.6	6.8	5.8	5.4	5.7	5.7	5.4	5.8	5.4	6.1	6.1	5.4
	100	7.3	7.5	6.3	5.9	6.2	6.2	5.9	6.3	5.9	6.6	6.6	5.9
2012	10	2.9	3.1	2.8	2.6	2.6	2.6	2.6	2.8	2.6	3.0	3.0	2.6
	20	3.8	4.1	3.7	3.4	3.4	3.4	3.4	3.7	3.4	3.9	3.9	3.4
	30	4.5	4.8	4.4	4.0	4.1	4.1	4.0	4.4	4.0	4.6	4.6	4.0
	50	5.5	5.9	5.4	4.9	5.0	5.0	4.9	5.4	4.9	5.7	5.7	4.9
	80	6.6	7.1	6.5	5.9	6.0	6.0	5.9	6.5	5.9	6.8	6.8	5.9
	100	7.3	7.8	7.1	6.4	6.6	6.6	6.4	7.1	6.4	7.5	7.5	6.4
Mean	10	2.9	3.1	2.7	2.5	2.6	2.6	2.5	2.7	2.5	2.9	2.9	2.5
	20	3.8	4.0	3.6	3.3	3.4	3.4	3.3	3.6	3.3	3.8	3.8	3.3
	30	4.5	4.7	4.2	3.9	4.0	4.0	3.9	4.2	3.9	4.4	4.4	3.9
	50	5.5	5.8	5.1	4.7	4.9	4.9	4.7	5.1	4.7	5.4	5.4	4.7
	80	6.7	7.0	6.2	5.7	5.9	5.9	5.7	6.2	5.7	6.6	6.6	5.7
	100	7.3	7.7	6.8	6.2	6.4	6.4	6.2	6.8	6.2	7.2	7.2	6.2

It is clear (Fig. 3) that Kalpa town shows the highest monthly mean wind speeds at 4.19 m/s and 3.79 m/s in May 2010 and 2012 respectively and the lowest mean wind speeds of 2.22 m/s and 2.06 m/s in November 2009 and December 2010 respectively. The yearly monthly mean wind speed data for Kalpa are found to deviate from the 5 years mean data by 6.17–8.53%. After Kalpa, Keylong and Nahan towns show the next highest mean wind speeds than other towns. The highest monthly mean wind speeds for Bilaspur are found to be 4.13 m/s and 4.06 m/s for June 2009 and May 2010 respectively whereas the lowest mean wind speeds of 1.69 m/s and 1.67 m/s occur in November 2010 and 2011 respectively. The yearly mean wind speed data for Bilaspur slightly deviates from 5 year mean wind speed by 14.85% and 10.96%. Dharmasala is little windier than Bilaspur. The mean, maximum and minimum wind speed data of 12 towns are given in Table 3.

It is observed that the monthly mean wind speeds start increasing from 1.4 m/s to 4.77 m/s and maximum mean wind speeds of 3–4.5 m/s are observed mostly during summer months (March, May and June). The lowest wind speeds in the range 1.4–2.5 m/s occur during winter months especially in November, December, and January. The annual mean wind speed variation over the period 2008–2012 for all towns is shown in Fig. 4.

It is observed that the annual mean wind speed varies from 2.97 m/s to 3.1 m/s in 2011 and 2012 for Kalpa town with a minimum and maximum deviations of 2.97% and 3.09% respectively from the five years mean value of 3.05 m/s. The results indicate that Kalpa is the most windy site, whereas Bilaspur is the least windy site with annual mean wind speed variation from 2.34 m/s to 2.56 m/s in 2011 and 2009 with minimum and maximum deviation of 9.36% and 0.02% from the five years mean value of 2.48 m/s respectively. The wind speeds at10 m height are not found suitable for power generation so the wind speeds are extrapolated to 20 m, 30 m, 50 m, 80 m, and 100 m using wind shear analysis so as to determine wind potential at these heights.

4.1.1. *Weibull and cumulative wind speed distributions*

Weibull and cumulative wind speed distributions derived from five years period (2008–2012) are shown in Fig. 5. It is observed that Weibull parameters k and c for Keylong are 3.2 and 3.2 m/s respectively with mean wind speed of 3 m/s available for 38.18% whereas for Kalpa the parameters are 2.48 and 3.39 m/s respectively with mean wind speed of 3 m/s available for 39.42% per year. Weibull parameters k and c for Shimla are found to be 2.97 and 3.01 m/s respectively with availability of wind speed 2.5 m/s for 38.44% per year. Weibull shape and scale parameters for Bilaspur are found as 2.63 and 2.79 m respectively with mean wind speed of 2.5 m/s available for 37.3% of time during the year. The shape and scale parameters are found as 2.98 and 2.87 m/s respectively for Chamba with mean wind speed of 2.56 m/s for 40.68%. The shape and scale parameters for Nahan are found as 2.53 and 3.21 m/s mean wind speed of 2.5 m/s for 31.53% during the year.

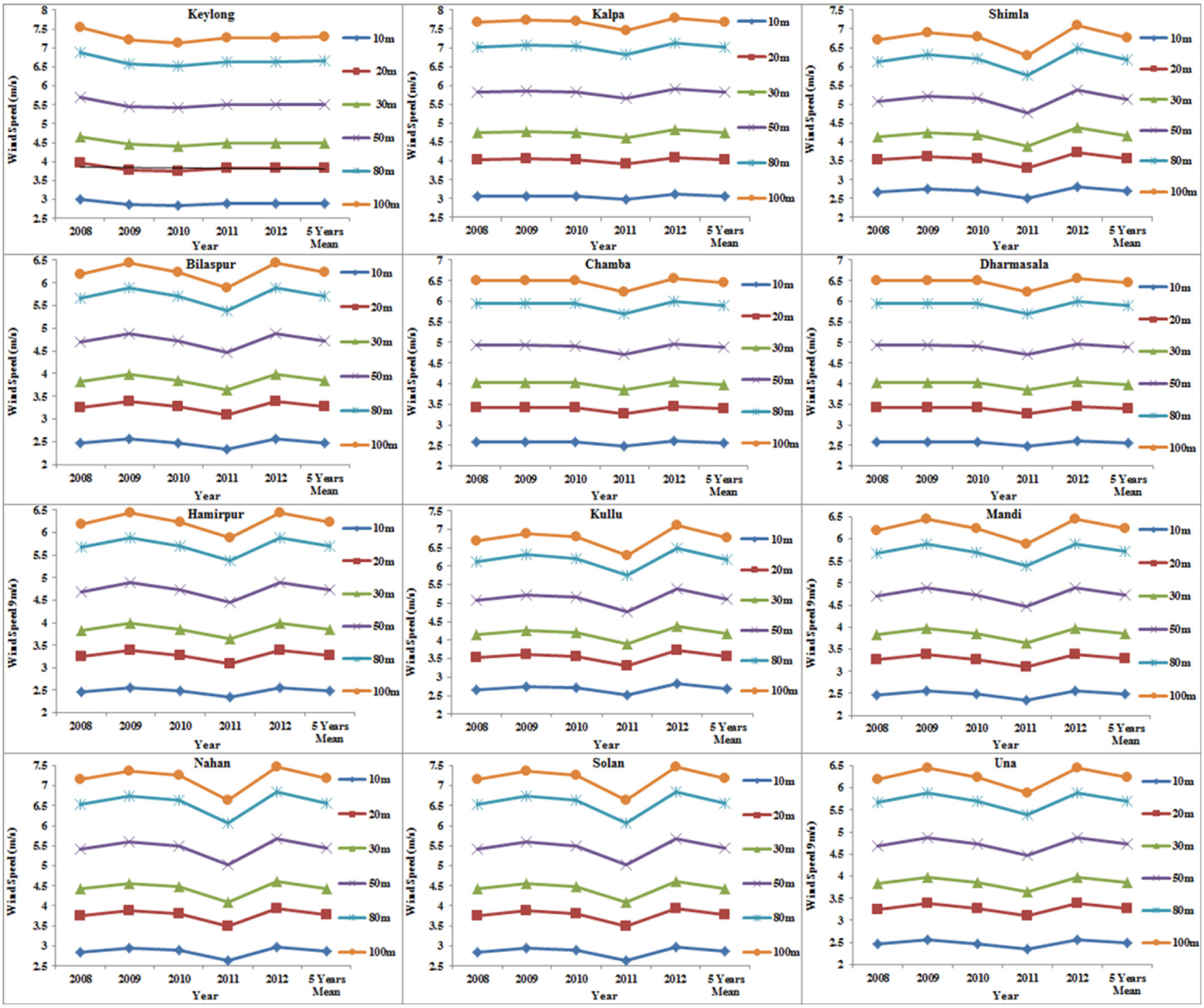

Fig. 7. Mean wind speed variation at 10 m, 20 m, 30 m, 50 m, 80 m, and 100 m heights for all the stations of H.P.

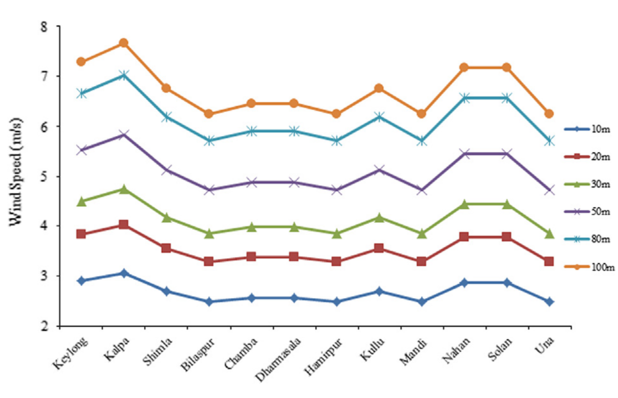

Fig. 8. Comparison of five years mean wind speeds at various heights for 12 towns.

The comparative variation of Weibull and cumulative probability density functions is shown for all towns of Himachal Pradesh in Fig.6.

Weibull shape parameter k and scale parameter c, mean power densities are calculated (Table 5) using WEPF method with inputs from Table 4.

The mean power density varied from 9.39 W/m^2 to 18.55 W/m^2 at 10 m with WEPF value range from 1.5 to 18.02.

4.2. Results of wind shear analysis

Using –Eq. (10),the wind shear analysis is carried out year wise for the five years period (2008–2012) at 20 m, 30 m, 50 m, 80 m and 100 m using power law with an exponent of 0.4 for all the stations of H.P. using wind data measured at 10 m height. The results are shown in Fig. 7.

The mean wind speed and wind power densities for the 12 locations are found to be in the range 3.9–4.7 m/s, 4.7–5.8 m/s, 5.7–7 m/s, 6.2–7.7 m/s and 14.09–22.15 W/m^2, 52.67–82.79 W/m^2, 97.23–152.82 W/m^2, 170.9–268.62 W/m^2, 223.37–351.1 W/m^2 at 30 m, 50 m, and 100 m heights respectively, thereby indicating good wind potential for building integrated micro-wind turbines, battery charging, water pumping, wind power generation in western Himalayan region.

The comparative variation of wind speeds at various heights for 12 locations is shown in Fig. 8. Analysis indicates that maximum mean wind speeds are observed for Kalpa, Keylang followed by Solan, Nahan, Shimla, Dharmasala, Bilaspur, Hamirpur, Una and Mandi towns. It is observed from the results that wind speed data

Table 6
Comparison of wind speeds and power densities at various heights for 12 towns.

S. No	Town	Parameter	Wind speed(m/s) and power density (W/m^2)at different heights				
			10 m	30 m	50 m	80 m	100 m
1	Keylong	v	2.90	4.99	5.52	6.61	7.28
		v_{max}	9.98	15.49	19.00	22.93	25.07
		v_{min}	0.89	1.38	1.69	2.04	2.24
		P	19.33	72.24	133.35	234.40	306.37
2	Kalpa	v	3.06	4.74	5.82	7.02	7.68
		v_{max}	8.14	12.63	15.50	18.70	20.45
		v_{min}	0.80	1.24	1.52	1.84	2.01
		P	21.28	79.52	146.79	258.01	337.23
3	Shimla	v	2.69	4.18	5.12	6.18	6.76
		v_{max}	6.01	9.33	11.44	13.81	15.10
		v_{min}	0.68	1.06	1.29	1.56	1.71
		P	16.32	60.99	112.58	197.88	258.65
4	Bilaspur	v	2.48	3.86	4.73	5.71	6.24
		v_{max}	8.44	13.10	16.07	19.39	21.20
		v_{min}	0.71	1.10	1.35	1.63	1.78
		P	14.09	52.67	97.23	170.90	223.38
5	Chamba	v	2.57	3.98	4.89	5.90	6.45
		v_{max}	6.68	10.37	12.72	15.35	16.78
		v_{min}	0.77	1.19	1.47	1.77	1.93
		P	14.12	52.78	97.43	171.25	223.83
6	Dharmasala	v	2.57	3.98	4.89	5.90	6.45
		v_{max}	6.68	10.37	12.72	15.35	16.78
		v_{min}	0.77	1.19	1.47	1.77	1.93
		P	14.12	52.78	97.43	171.25	223.83
7	Hamirpur	v	2.48	3.86	4.73	5.71	6.24
		v_{max}	8.44	13.10	16.07	19.39	21.20
		v_{min}	0.71	1.10	1.35	1.63	1.78
		P	14.09	52.67	97.23	170.90	223.38
8	Kullu	v	2.69	4.18	5.12	6.18	6.76
		v_{max}	6.01	9.33	11.44	13.81	15.10
		v_{min}	0.68	1.06	1.29	1.56	1.71
		P	16.32	60.99	112.58	197.88	258.65
9	Mandi	v	2.48	3.86	4.73	5.71	6.24
		v_{max}	8.44	13.10	16.07	19.39	21.20
		v_{min}	0.71	1.10	1.35	1.63	1.78
		P	14.09	52.67	97.23	170.90	223.38
10	Nahan	v	2.86	4.43	5.44	6.57	7.18
		v_{max}	8.17	12.68	15.55	18.77	20.52
		v_{min}	0.66	1.02	1.26	1.52	1.66
		P	22.15	82.79	152.83	268.63	351.11
11	Solan	v	2.86	4.43	5.44	6.57	7.18
		v_{max}	8.17	12.68	15.55	18.77	20.52
		v_{min}	0.66	1.02	1.26	1.52	1.66
		P	22.15	82.79	152.83	268.63	351.11
12	Una	v	2.48	3.86	4.73	5.71	6.24
		v_{max}	8.44	13.10	16.07	19.39	21.20
		v_{min}	0.71	1.10	1.35	1.63	1.78
		P	14.09	52.67	97.23	170.90	223.38

Table 7
Comparison of wind characteristics at 10 m and 30 m heights for 12 towns.

S. No	Towns	Height													
		10 m							30 m						
		v_m (m/s)	WEPF	k	c (m/s)	v_{mp} (m/s)	v_{me} (m/s)	P_d (W/m^2)	v_m (m/s)	WEPF	k	c (m/s)	V_{mp} (m/s)	V_{me} (m/s)	P_d (W/m^2)
1	Keylong	2.90	1.29	3.20	3.24	2.88	3.77	19.33	4.50	1.29	3.20	5.02	4.47	5.85	72.24
2	Kalpa	3.06	1.22	3.49	3.40	3.08	3.87	21.28	4.74	1.22	3.49	5.27	4.78	6.00	79.52
3	Shimla	2.69	1.37	2.98	3.01	2.63	3.58	16.32	4.18	1.37	2.98	4.68	4.08	5.56	60.99
4	Bilaspur	2.48	1.50	2.64	2.80	2.33	3.46	14.09	3.86	1.50	2.64	4.34	3.62	5.37	52.67
5	Chamba	2.57	1.36	2.98	2.87	2.51	3.41	14.12	3.98	1.36	2.98	4.46	3.89	5.30	52.78
6	Dharmashala	2.57	1.36	2.98	2.87	2.51	3.41	14.12	3.98	1.36	2.98	4.46	3.89	5.30	52.78
7	Hamirpur	2.48	1.50	2.64	2.80	2.33	3.46	14.09	3.86	1.50	2.64	4.34	3.62	5.37	52.67
8	Kullu	2.69	1.37	2.98	3.01	2.63	3.58	16.32	4.18	1.37	2.98	4.68	4.08	5.56	60.99
9	Mandi	2.48	1.50	2.64	2.80	2.33	3.46	14.09	3.86	1.50	2.64	4.34	3.62	5.37	52.67
10	Nahan	2.86	1.55	2.54	3.22	2.64	4.05	22.15	4.43	1.55	2.54	5.00	4.10	6.28	82.79
11	Soaln	2.86	1.55	2.54	3.22	2.64	4.05	22.15	4.43	1.55	2.54	5.00	4.10	6.28	82.79
12	Una	2.48	1.50	2.64	2.80	2.33	3.46	14.09	3.86	1.50	2.64	4.34	3.62	5.37	52.67

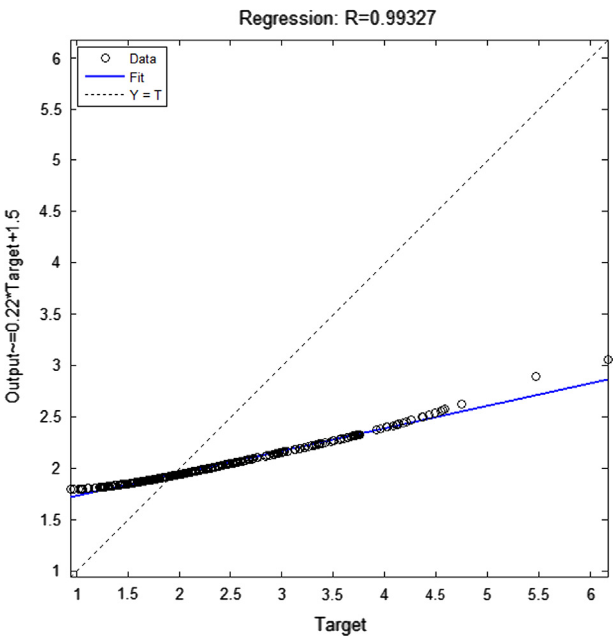

Fig. 9. Regression plot for prediction of measured wind data.

for Kullu are found similar to that of Shimla and Hamirpur, Mandi and Una are same as that of Bilaspur. The wind data for Dharmasala and Solan are found to be same as that of Chamba and Nahan respectively. This is due to limitation of NASA data which gives similar values for locations which have latitude and longitude difference $<1^{\circ}$.The wind speeds and mean power densities at different heights for 12 towns are shown in Table 6.

The other determined wind characteristics (WEPF, k, c, V_{mp}, V_{me}, f, and F) at different heights are not displayed in Table 6 due to space limitation. It is observed that the energy pattern factor, Weibull shape parameter k and cumulative probability function values remain same for all the towns. The wind characteristics, Weibull parameters and WEPF values at 10 m and 30 m are given for comparison sake in Table 7. It is observed that the wind speed increases at 30 m as expected whereas the WEPF factor remains same at both heights. The Weibull shape factor k also remains same for both heights but parameter c varies as it is velocity dependent.

4.3. Prediction of measured wind speed data

A correlation between measured data of Hamirpur and NASA data is developed for the estimation of wind data for various locations in the region. The Center for Energy and Environment at National Institute of Technology, Hamirpur has an automatic wind data

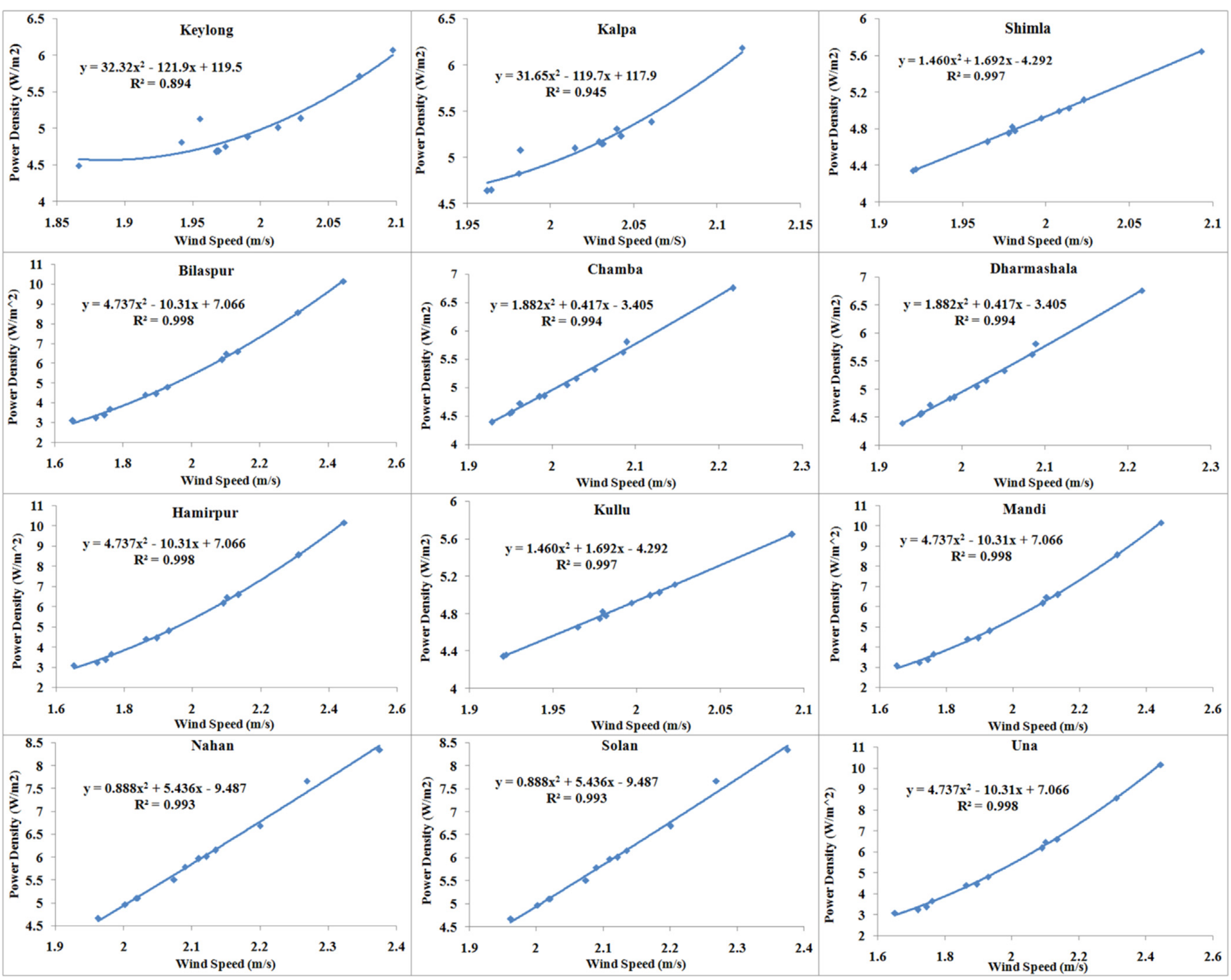

Fig. 10. Scatter plot between monthly mean wind power densities and monthly mean wind speeds for all sites using second order polynomial fit during the period of December 2012–November 2013.

Table 8
Monthly annual prediction of measured wind speeds, WEPF's, measured WPD's, and annual fitness coefficient for all stations during period of December 2012–November 2013.

Station	Parameter	Dec-12	Jan-13	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Annual	Fitness coefficient (R^2)
Keylong	v (m/s)	1.94	1.87	2.10	2.07	1.97	1.99	1.96	2.01	2.03	1.97	1.97	1.97	1.99	0.894
	WEPF	1.07	1.13	1.07	1.05	1.01	1.01	1.12	1.00	1.00	1.00	1.00	1.00	1.04	
	P_d (W/m^2)	4.81	4.49	6.07	5.71	4.75	4.88	5.13	5.01	5.14	4.69	4.68	4.69	5.00	
Kalpa	v (m/s)	2.03	1.98	2.11	1.98	2.03	2.06	2.04	2.04	2.03	1.96	2.01	1.96	2.02	0.945
	WEPF	1.01	1.06	1.07	1.01	1.00	1.01	1.02	1.00	1.00	1.00	1.02	1.00	1.02	
	P_d (W/m^2)	5.17	5.08	6.18	4.83	5.15	5.38	5.31	5.23	5.15	4.65	5.10	4.64	5.15	
Shimla	v (m/s)	1.98	2.00	2.02	2.01	1.98	2.09	2.01	1.98	1.96	1.92	1.92	1.98	1.99	0.997
	WEPF	1.02	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.01	
	P_d (W/m^2)	4.82	4.92	5.11	5.00	4.79	5.65	5.02	4.78	4.66	4.34	4.36	4.75	4.85	
Bilaspur	v (m/s)	1.93	1.87	2.10	2.31	2.14	2.44	2.09	1.76	1.65	1.72	1.75	1.90	1.97	0.998
	WEPF	1.09	1.11	1.14	1.13	1.11	1.13	1.10	1.09	1.12	1.04	1.04	1.07	1.16	
	P_d (W/m^2)	4.80	4.40	6.48	8.56	6.59	10.15	6.17	3.67	3.09	3.23	3.37	4.45	5.41	
Chamba	v (m/s)	1.96	1.99	2.09	2.03	2.08	2.22	2.05	1.99	1.95	1.93	1.95	2.02	2.02	0.994
	WEPF	1.02	1.01	1.04	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.01	
	P$_d$ (W/m^2)	4.73	4.86	5.81	5.16	5.62	6.75	5.33	4.84	4.55	4.40	4.57	5.05	5.14	
Dharmashala	v (m/s)	1.96	1.99	2.09	2.03	2.08	2.22	2.05	1.99	1.95	1.93	1.95	2.02	2.02	0.994
	WEPF	1.02	1.01	1.04	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.01	
	P_d (W/m^2)	4.73	4.86	5.81	5.16	5.62	6.75	5.33	4.84	4.55	4.40	4.57	5.05	5.14	
Hamirpur	v (m/s)	1.93	1.87	2.10	2.31	2.14	2.44	2.09	1.76	1.65	1.72	1.75	1.90	1.97	0.998
	WEPF	1.09	1.11	1.14	1.13	1.11	1.13	1.10	1.09	1.12	1.04	1.04	1.07	1.16	
	P_d (W/m^2)	4.80	4.40	6.48	8.56	6.59	10.15	6.17	3.67	3.09	3.23	3.37	4.45	5.41	
Kullu	v (m/s)	1.98	2.00	2.02	2.01	1.98	2.09	2.01	1.98	1.96	1.92	1.92	1.98	1.99	0.997
	WEPF	1.02	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.01	
	P_d (W/m^2)	4.82	4.92	5.11	5.00	4.79	5.65	5.02	4.78	4.66	4.34	4.36	4.75	4.85	
Mandi	v (m/s)	1.93	1.87	2.10	2.31	2.14	2.44	2.09	1.76	1.65	1.72	1.75	1.90	1.97	0.998
	WEPF	1.09	1.11	1.14	1.13	1.11	1.13	1.10	1.09	1.12	1.04	1.04	1.07	1.16	
	P_d (W/m^2)	4.80	4.40	6.48	8.56	6.59	10.15	6.17	3.67	3.09	3.23	3.37	4.45	5.41	
Nahan	v (m/s)	2.11	2.09	2.12	2.20	2.27	2.38	2.13	2.02	2.00	2.02	1.96	2.07	2.11	0.993
	WEPF	1.04	1.03	1.03	1.02	1.07	1.02	1.03	1.01	1.01	1.01	1.01	1.01	1.02	
	P_d (W/m^2)	5.97	5.79	6.01	6.69	7.67	8.35	6.15	5.10	4.96	5.10	4.67	5.51	6.00	
Solan	v (m/s)	2.11	2.09	2.12	2.20	2.27	2.38	2.13	2.02	2.00	2.02	1.96	2.07	2.11	0.993
	WEPF	1.04	1.03	1.03	1.02	1.07	1.02	1.03	1.01	1.01	1.01	1.01	1.01	1.02	
	P_d (W/m^2)	5.97	5.79	6.01	6.69	7.67	8.35	6.15	5.10	4.96	5.10	4.67	5.51	6.00	
Una	v (m/s)	1.93	1.87	2.10	2.31	2.14	2.44	2.09	1.76	1.65	1.72	1.75	1.90	1.97	0.998
	WEPF	1.09	1.11	1.14	1.13	1.11	1.13	1.10	1.09	1.12	1.04	1.04	1.07	1.16	
	P_d (W/m^2)	4.80	4.40	6.48	8.56	6.59	10.15	6.17	3.67	3.09	3.23	3.37	4.45	5.41	

monitoring station. The time series measured wind data of Hamirpur for the period December 2012–November 2013 are used to develop the correlation using Matlab software. NASA wind data [33] at 10 m height are extrapolated to 18.5 m height at which data are measured for Hamirpur. The regression plot is shown in Fig. 9. The equation for measured wind speed in terms of NASA wind speed data is obtained as

$$Y_{Measured} = -0.0003X_{NASA}^6 + 0.0042X_{NASA}^5 - 0.0166X_{NASA}^4 - 0.0097X_{NASA}^3 + ...0.2212X_{NASA}^2 - 0.3147X_{NASA} + 1.9124 \quad (11)$$

The root mean square error (RMSE) is found to be 0.3855 and correlation coefficient (R^2) as 92.61%, which means that almost 92.61% of the input data is covered and well fitted on the regression plot within the acceptable limits of 5% with a RMSE of 0.38855. The desirable conditions for adjustable parameter RMSE value should be minimum (almost equal to zero) and correlation coefficient value should be maximum (i.e. 100%) as much as possible. Eq. (11) can be used for the estimation of measured wind speeds with better accuracy for any location in the region.

4.4. Testing of WEPF method

The available measured data at the site Hamirpur for one year period during December 2012–November 2013 are used to test WEPF method with a typical annual value of WEPF as 1.15. The plot is drawn between the power density (P) on the dependent axis and monthly mean wind speed (v) on the independent axis as shown in Fig. 10. The data are fitted through a second order polynomial fitting of P versus v with an adjustable coefficient R^2 (or fitness coefficient) of 0.9983.

The measured wind speeds are predicted by using model Eq. (11) obtained from the time series measured data available at the site Hamirpur for remaining stations. The data has been best fitted for all stations through a second order polynomial fit between predicted measured power density taken on the dependent axis and predicted measured wind speed taken on the independent axis with an adjustable coefficient R^2 (or fitness coefficient), except for Keylong station as shown in Table 8.

5. Conclusions

In this study an overview of wind resource assessment methods along with assessment of the wind potential of 12 locations in the western Himalayan Indian state of Himachal Pradesh is presented using Wind Energy Factor method. The maximum mean wind speeds and wind power densities are observed for Kalpa, Keylong followed by Nahan, Solan Shimla, Kullu, Chamba,

Dharmasala, Bilaspur, Hamirpur, Mandi and Una towns. The maximum wind speeds are found during summer months and minimum during winter months for all locations. The mean wind speeds and mean wind power densities at hub heights greater than 80 m are found to vary from 4.7 to 7.7 m/s and 200 W/m^2 to 350 W/m^2 respectively; thereby indicating good wind potential for wind power generation in Kalpa (Distt Kinnaur) and Keylong (Lahaul and Spiti) in the western Himalayan region. Apart from the Kalpa, all the locations have both wind speeds and wind power densities belonging to class-1 at 10 m, 30 m, and 50 m heights. Kalpa is having class-2 wind speeds (in between 5.6 m/s and 6.4 m/s) at 50 m followed by Keylong and Nahan with class-2 wind speeds between 5.71 m/s and 5.67 m/s.

Although the present study is only a preliminary investigation to estimate the wind energy potential of the region yet it indicates good potential for utilizing micro-turbines for roof integrated, stand alone and wind energy based hybrid systems. Besides, the study also provides inputs for formulating suitable policy measures for the promotion of wind energy generators for rural and remote areas.

As a follow up of the present study, suitable locations in the region including hill tops and valleys which are expected to have good wind power potential need to be identified using wind climate knowledge of local people, folklores, biological indicators and topography analysis. Based on this analysis detailed wind resource assessment of the identified sites can be carried out by establishing automatic wind monitoring stations. The present study will be useful in moving towards this direction.

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